Life cycle assessment of prefabricated timber frame 'open-renovation-systems' for rooftop extensions

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Abstract: Compact building design is a key challenge in Flanders. Additional housing is required due to the growing Flemish population combined with decreasing household size. Seen the current problems of urban sprawl, densification of the current residential area offers a solution to address these extra housing needs and to avoid further fragmentation of remaining valuable open space. Therefore, the emphasis in this research is on designing and evaluating affordable and innovative 'open-renovation-systems' for low-energy rooftop extensions on residential buildings. In preliminary research, a screening of a current Belgian timber frame system for a rooftop extension has been made at both the element and building level through a life cycle assessment. The wooden based parts of the timber frame were identified as hotspots. This paper builds further on these results and focuses on how to reduce the environmental impact of prefabricated timber frame renovation systems. The results of this paper show that optimizing the wooden sections in timber frame walls by means of using I-joists instead of solid studs can slightly reduce the environmental impact. Furthermore, this study confirmed that the modelling of the wood preservatives has an important influence on the results and hence a correct modelling is necessary.

Keywords: Life Cycle Assessment (LCA), environmental impact, timber frame, rooftop extensions

Introduction

Compact building design is one of the current key challenges in Flanders. Despite a high population density, the density measured within the residential area of Flanders is very low compared to other European countries (Eurostat, 2012). Moreover, due to the growing Flemish population combined with decreasing household size, additional housing is still required (Ryckewaert et al., 2011). Densification of the current built-up area offers a solution to address these housing needs without further fragmentation of remaining valuable open space.

This paper is part of an ongoing research which deals with the aforementioned issues and focuses on designing and evaluating prefabricated timber frame systems for rooftop extensions on residential buildings. The choice for prefabricated timber frame systems is based on the key requirements of minimal disturbance for the neighbourhood and inhabitants and of not overloading the existing structure including foundations (i.e. need for a lightweight structure). In a preliminary research step (Wijnants et al., 2016) a Belgian rooftop extension in timber frame has been analysed over a lifespan of 60 year. The timber and timber-based parts in the timber frame wall were identified as the parts with the highest environmental impact of the considered timber frame wall. This high impact is mainly due to the end-of-life (EOL) processes of these parts. Analysis of the generic datasets used for the end-of-life processes of treated wood learned that it includes chromium. Chromium is however no longer used in Belgium as preservation for construction wood. As untreated wood had a 50% lower environmental impact than treated wood, further research on the current wood preservation used in Belgium was needed.

The humidity, temperature and climate variations are the primary factors affecting the risk of wood degradation. (NBN EN 335, 2013) Depending on the type and duration of exposure to these factors and the possibility of drying of the timber, five use classes are distinguished. Construction wood is classified in use class 2. The wood in this use class is wood not in contact with soil and normally not exposed to weather influences nor to leaching. A temporary wetting is however possible. (NBN EN 335, 2013) This means that insects and moisture are possible threats for the wood and wood preservation is often necessary.

There are no mandatary Belgian standards regarding wood preservation in the private sector, but technical specifications are elaborated after a broad consultation of a wide range of major actors in the sector and are considered as “good practice” to be followed by architects and contractors. These technical specifications are published in STS 04.03 (Federale overheidsdienst economie, K.M.O., middenstand en energie, 2009).

In Belgium, wood preservation based on immersion process ‘A2.1/T3: behandeling door lange drenking’ is currently most common for timber frame constructions (Dobbels, 2016; Federale overheidsdienst economie, K.M.O., middenstand en energie, 2009). This treatment involves submerging of wood into a dipping tank filled with wood preservative for a period of at least one hour (Federale overheidsdienst economie, K.M.O., middenstand en energie, 2009).

The main aim of this paper is twofold. Firstly, the environmental impact calculations of an organic solvent based wood preservative for treatment process A2.1/T3 is assessed and described in detail. Secondly, the potential environmental impact reduction by means of changing the type and dimensions of the timber frame studs is analysed.

Methodology

The assessment of the life cycle environmental impact of timber frame elements is based on the Belgian MMG Life Cycle Assessment (LCA) method (Allacker et al., 2013). The MMG method follows an integrated life cycle approach, as recommended by the European standards EN 15804+A1 (CEN, 2014) and EN 15978 (CEN, 2011) for the evaluation of construction products and buildings. The entire life cycle of the building is considered, namely initial stage, use stage and end-of-life (EOL) stage. The MMG method includes two sets of impact categories: (1) the ones of the CEN standards (Global warming, Depletion of the stratospheric ozone layer, Acidification of land, Eutrophication freshwater and marine, Photochemical oxidant formation, Abiotic depletion of non-fossil resources, Abiotic depletion of fossil resources) and (2) seven additional impact categories, referred to as CEN+ indicators (Human toxicity, Particulate matter formation, Ionising radiation, Ecotoxicity, Land occupation, Land transformation). The LCA results are expressed in external environmental costs. The environmental impact calculations are based on the generic database Ecoinvent v3.2 (Ecoinvent, 2014), transport and end-of-life processes are adapted to the Belgian context. The operational energy use is estimated based on the Equivalent Degree Days (EDD) method. This method follows a static approach based on average solar radiation data for two characteristic months of the year, i.e. March and December (Diensten voor de programmatie van het wetenschapsbeleid, 1984). An average of 1200 equivalent degree days was determined as an appropriate value for well-insulated residential buildings in Belgium

(Allacker, 2010) and hence this value is used for the energy use estimation. In this study, a condensing gas boiler is considered as energy source for heating. A detailed description of the MMG LCA method can be found in the MMG report (Debacker et al., 2012). At the Architectural Engineering research division of the KU Leuven, the MMG method was translated into a calculation tool which was used for the analysis presented in this paper.

As indicated in the introduction, the environmental cost caused by the common wood preservation treatment in Belgium is still lacking in the current MMG database. Therefore, an organic solvent based wood preservative in accordance with A2.1 processes is modelled and added to the MMG database. The environmental impact due to production of this organic solvent based wood preservative is calculated based on the Ecoinvent record (Ecoinvent centre, 2014) '*Wood preservation, dipping/immersion method, organic solvent based, indoor use, occasionally wet {RER} | wood preservation, dipping/immersion, solvent-based preservative, indoor use, occasionally wet | Alloc Rec, U*'. The wood preservative inventoried in this dataset is an organic solvent-based primer for use class 2 and contains 0,55% Iodopropynyl Butyl Carbamate (IPBC), 0,15% Permethrine and 0,6% Tebuconazole as active agents and a 100% v/v concentration for application. This record is adapted according to the composition of the Belgian wood preservative AXIL MULTI (ATG 12/2294) (Belgische Unie voor technische goedkeuring in de Bouw, 2013). The quantity active agents, expressed in mass fraction, of this wood preservative are: 0,17% Propiconazole, 0,3% Tebuconazole, 0,1% Cypermethrine and 0,3% IPBC. As the production of Propiconozale is not in the Ecoinvent database, Tebuconazole is used as a proxy as both are triazole fungicides (The American Phytopathological Society, 2017). The quantity of active agents in the adapted record is less than in the original Ecoinvent record and therefore the quantity of solvent is also adapted accordingly. The record used covers the impregnation of wood in open tank and considers that the wood preservative penetrates the wood three millimetres with a critical concentrate value of 40 kg/m³ in this treated zone. The amount of wood preservative in 1 m² timber frame wall is hence dependant on the dimensions of the timber frame studs.

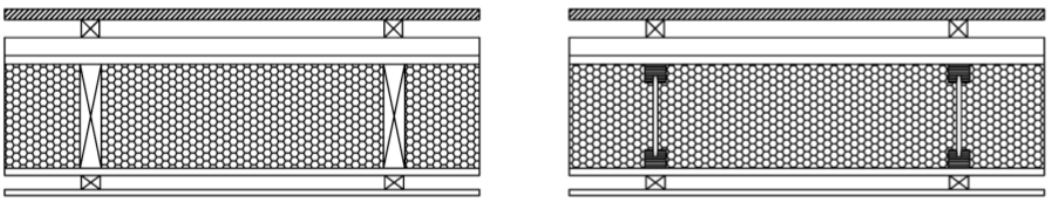
Due to a lack of end-of-life (EOL) processes in Ecoinvent for wood treated with preservatives, an estimation of the environmental impact due to incineration is made based on available data in literature. For the EOL incineration of the organic solvent based treated wood, the emissions to air are calculated based on the constituents of the wood preservative which are added in the production dataset. Based on Salthammer et al. (1995) and Tame et al. (2007), the emissions due to the formation of polychlorinated Dibenzo-p-Dioxins (PCDD) and Polychlorinated Dibenzofurans (PCDD/F) are added. The Ecoinvent dataset of untreated wood is used as proxy for landfilling. The EOL scenario of wood is assumed identical to these in the MMG method: 5% of the treated wood is landfilled, 95% is incinerated. Furthermore, in line with the MMG method, it is assumed that the EOL processes occur in Belgium. The energy mixes in the standard Ecoinvent EOL datasets are therefore replaced by their Belgian equivalent. The EOL processes for incineration of laminated timber, oriented strand board (OSB) and wood fibre are currently lacking in the Ecoinvent database. An estimation of their environmental impact is based on the required amount of glue during production and on available data in literature (Moreno et al., 2017; Risholm-Sundman and Vestin, 2005). Pollution due to the emission of nitrogen oxide and formaldehyde are considered. The same assumptions are made as described above for the EOL of organic solvent based treated wood.

Results

A timber frame wall with different stud types and dimensions has been analysed over a lifespan of 60 year to assess the potential environmental impact reduction by optimizing its bearing structure. The composition of the analysed timber frame wall element is described in Table 1. The internal and external finishes are assumed identical in all cases, the dimensions of the timber frame and insulation between the timber studs differ in all cases considered. The composition of the wall with solid studs of 14,5 cm slightly differs in order to fulfil the current Energy Performance (EPB) requirements in Belgium. Two possible solutions are analysed. In the first solution, the wood fibre board has a thickness of 40 mm instead of 18 mm. In the second solution, an extra insulation layer of 60 mm in XPS and a damp open foil is added. The U-value of the latter solution is identical to the U-value of a timber frame wall with solid studs of 24,5 cm. Solid wooden studs are compared with I-joists consisting of laminated veneer lumber flanges and a web with a thickness of 10 mm in OSB. The analysed dimensions of the studs as well as their U-value are provided in Figure 1. The dimensions of the solid studs are based on commonly used timber frame kits in Belgium. The dimensions of the I-joists are based on the available dimensions on the market and as close as possible to the dimensions of the solid studs in order to make a useful comparison between both. The environmental cost is expressed in euro per m² timber frame element.

Table 1. Overview of the wall compositions analysed

Timber frame wall
External finishes - wooden claddings - larix (thickness 22 mm) - ventilated cavity
External finishes - support structure for wooden claddings - wood Belgian mix - 38 x 38 mm - each 600 mm
External finishes - XPS (only for stud 14,5 cm (XPS)) - 60 mm
External finishes - wood fibre board - 18 mm (except for stud 14,5 cm (WFB): thickness 40 mm)
Thermal insulation between timber frame - glass wool
Timber frame
Internal finishes - OSB board - 15 mm
Internal finishes - support structure for boards - wood Belgian mix - 22 x 47 mm
Internal finishes - gypsum board - 12,5 mm - screwed - width 600 mm
Internal finishes - painting on gypsum board - acrylic paint



Solid stud 4,5*14,5cm WFB (U-value: 0,24 W/m²K)
Solid stud 4,5*14,5cm XPS (U-value: 0,18 W/m²K)
Solid stud 4,5*19,5cm (U-value: 0,22 W/m²K)
Solid stud 4,5*24,5cm (U-value: 0,18 W/m²K)

I-joist 4,5*16cm (U-value: 0,22 W/m²K)
I-joist 4,5*20cm (U-value: 0,18 W/m²K)
I-joist 4,5*24cm (U-value: 0,15 W/m²K)

Figure 1. Description of the timber frame compositions analysed

The life cycle environmental cost of the seven timber frame variants analysed is shown in Figure 2. The walls composed of wooden studs of 19,5 cm and 24,5 cm have an equal impact regarding material use than their equivalent timber frame walls composed of I-joists. The timber frame walls composed of solid studs of 14,5 cm have a 3% higher impact than their equivalent I-joist and an equal material use impact than the wall composed of solid studs of

19,5 cm. These higher material impacts are due to the impact of the thicker wood fibre board or extra XPS board in order to fulfil the current EPB requirements in Belgium, as described above. The environmental impact due to operational energy use is lower for the I-joists, compared to their equivalent solid studs, respectively 8%, 17% and 15% lower. On the contrary, the solution composed of solid studs of 14,5 cm and an extra XPS board has a 17% lower impact than its equivalent wall with I-joists. The life cycle environmental costs of the walls composed of I-joists is 5% - 6% lower compared to the walls with solid studs, except when compared to the solid stud with XPS insulation (i.e. the I-joist solution has a 4% higher life cycle environmental cost). Comparing both solutions of the wall composed of studs of 14,5 cm, the extra insulation layer of XPS is environmentally preferable. Compared with the solid wall studs of 24,5 cm which has the same U-value, the solution with XPS is preferable due to a lower material impact. Besides, the latter solution results in 4 cm thinner wall.

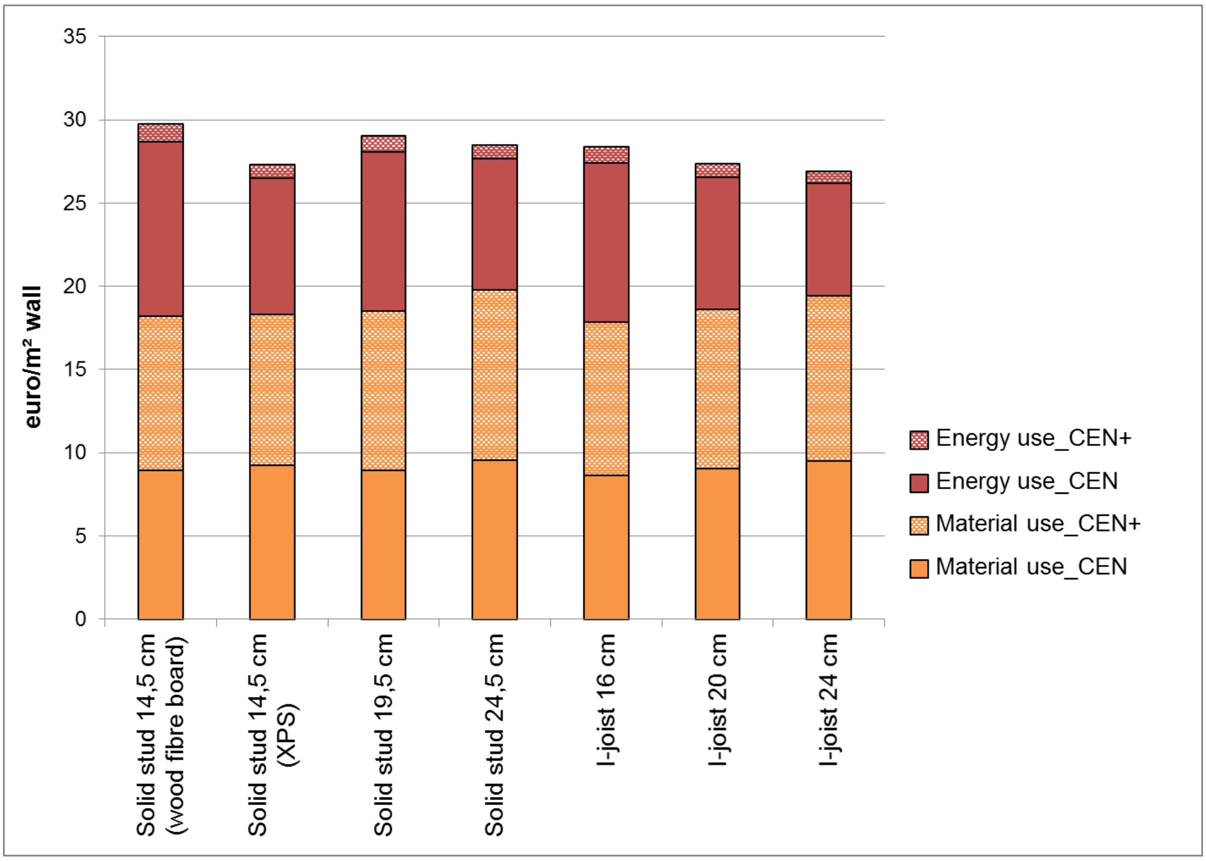


Figure 2. Environmental Life Cycle Cost, subdivided in material use and energy use, expressed in euro/m² wall

Moreover, Figure 2 shows that using solid studs or I-joists of respectively 24,5 cm and 24 cm instead of 19,5 cm and 20 cm does not generate a high environmental impact reduction. The environmental life cycle impact of the wall with the I-joists of 24 cm is only slightly (2%) lower than the wall composed of I-joists of 20 cm. However, using insulation materials with a different thermal conductivity may lead to other conclusions. In the subsequent paragraphs, a detailed comparison between the environmental impact of timber frame walls composed of solid studs and I-joists is made based on solid studs of 19,5 cm and I-joists of 20 cm.

Figure 3 shows the environmental impact per life cycle phase. As described above, the environmental cost for the operational energy use is 17% lower in case of a timber frame wall composed of I-joist. This is due to the higher insulation fraction and lower wood fraction. The other life cycle phases have an equal environmental impact in both wall compositions. Figure 4 shows the environmental cost per life cycle phase, but considers only 1 m² of wooden framework (not the complete wall composition). Despite a lower (11%) production impact for I-joists, the EOL cost is only 5% lower for the I-joist. This is due to the higher impact of municipal incineration due to the glue in the laminated timber flanges and OSB web of the I-joists. The environmental impact for waste transport is 35% lower for I-joists, due to a lower amount of wood that has to be transported to waste disposal.

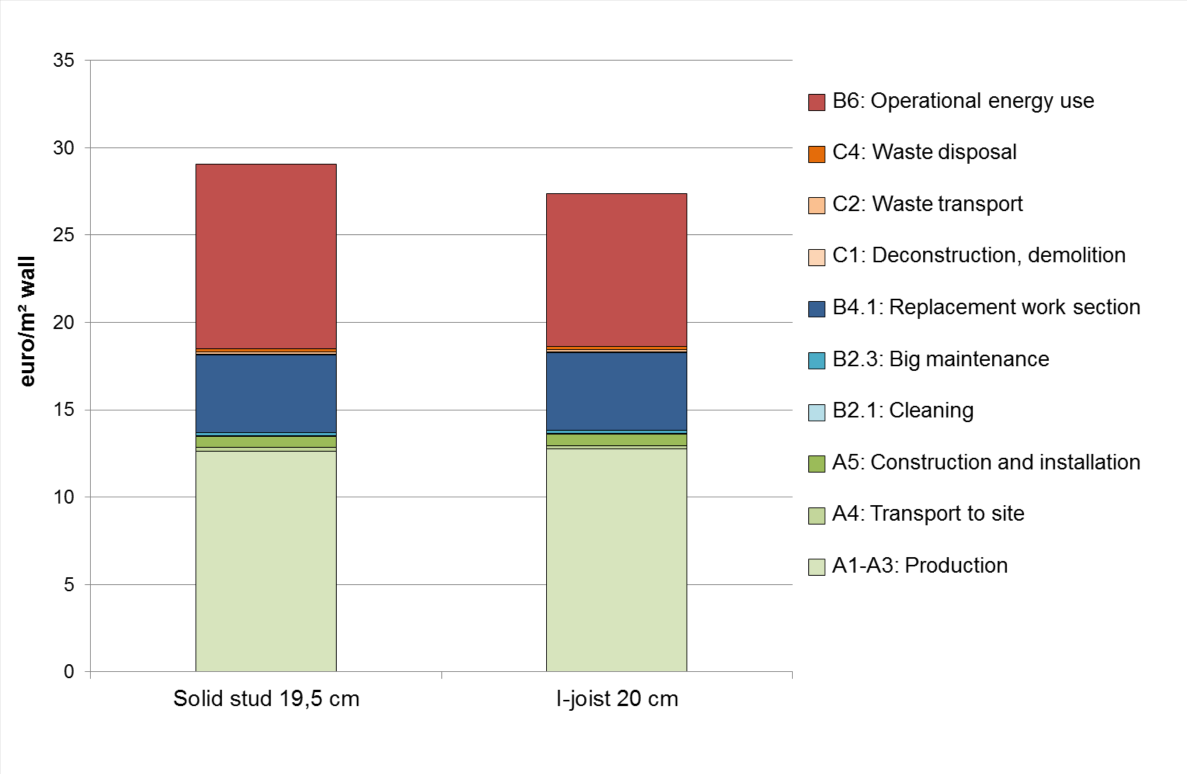


Figure 3. Environmental Life Cycle Cost of a timber frame wall with solid studs of 4,5*19,5cm (left), and a timber frame wall with I-joists of 4,5*20cm (right), subdivided per life cycle phase, expressed in euro/m² wall

In Figure 5 the environmental impact per work section is provided. In both cases, the wood fibre board has the highest environmental life cycle cost, namely 31% of the total life cycle cost. In case of a timber frame construction composed of I-joists of 19,5 cm, the insulation has a 16% higher environmental cost. Despite the 12% lower life cycle cost of the timber frame composed of I-joists, the total material life cycle cost is equal in both cases due to the higher amount of insulation material in the timber frame composed of I-joists.

Furthermore, this study confirmed that using the existing MMG records for treated wood which are based on chromium preserved wood leads to an overestimation of the environmental impact. The modelled organic solvent based treated wood in this study has only a 6% higher cost than untreated wood, while the chromium preserved wood has a 105% higher environmental cost than untreated wood. Changing the wooden sections in timber frame walls can slightly reduce the total environmental impact up to 10% in the cases considered.

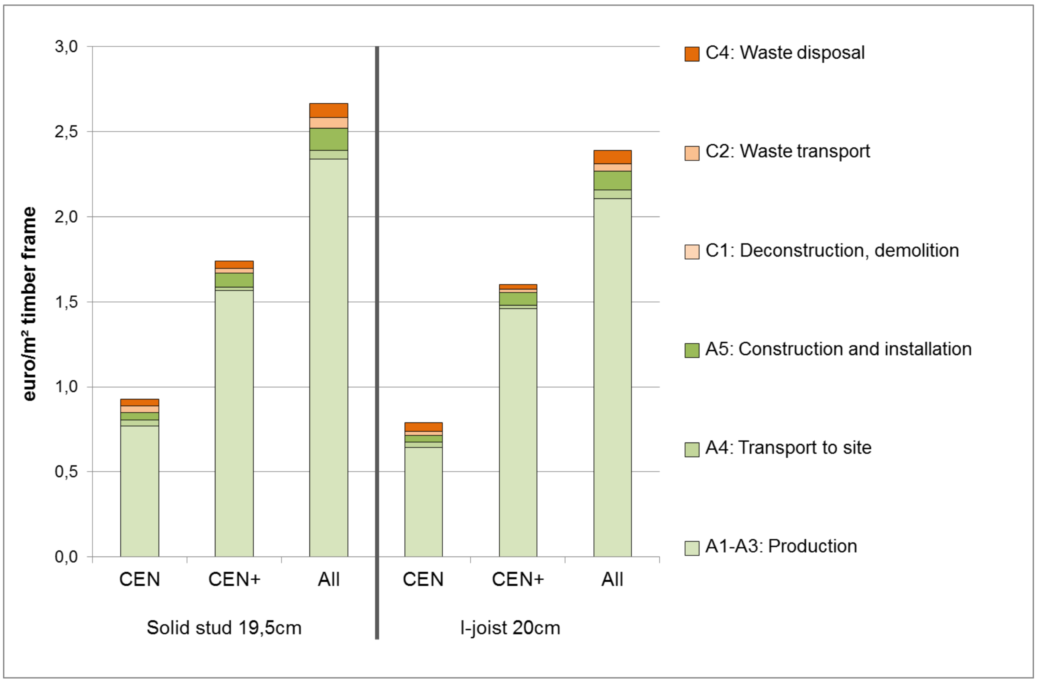


Figure 4. Environmental Life Cycle Cost of 1m² timber frame with solid studs of 4,5*19,5cm (left), and a timber frame with I-joists of 4,5*20cm (right), subdivided per life cycle phase, expressed in euro/m² timber frame

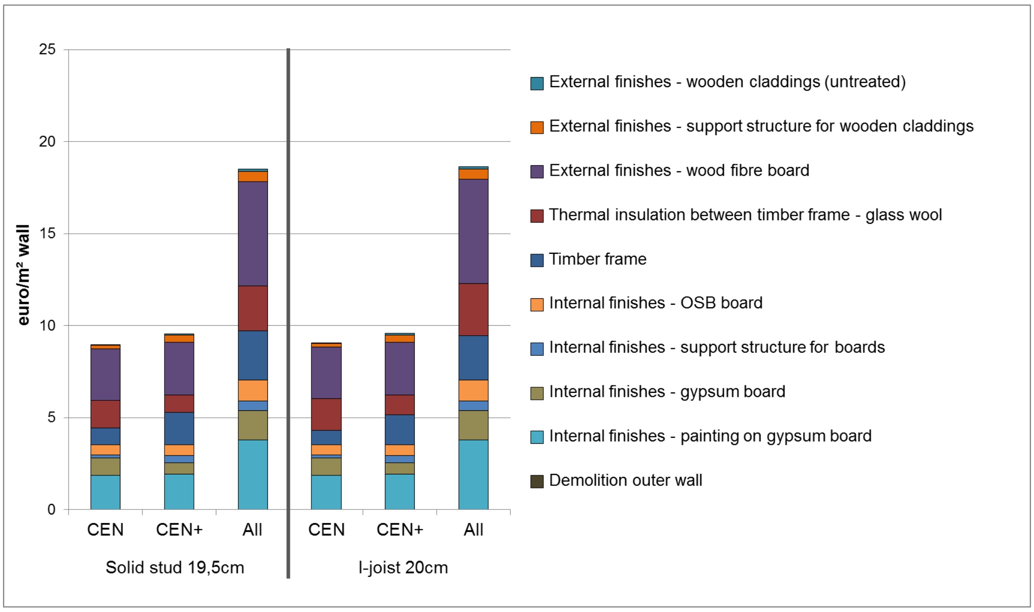


Figure 5. Environmental Life Cycle Cost of a timber frame wall with solid studs of 4,5*19,5cm (left), and a timber frame wall with I-joists of 4,5*20cm (right), subdivided per work section, expressed in euro/m² wall

Conclusion and recommendations

In this paper, two aspects in evaluating and optimizing the environmental cost of timber frame systems is analysed. Firstly, the environmental impact calculations of a commonly used organic solvent based wood preservative in Belgium for treatment process A2.1/T3 is modelled and described in detail. Secondly, the potential environmental impact reduction by means of changing the type and dimensions of the timber frame studs is assessed.

This study confirmed that a correct modelling of the wood preservative is necessary. The Ecoinvent records for treated wood which are based on chromium preserved wood lead to an overestimation of the environmental impact of more than 100% and should not be used for wood in the Belgian context.

Changing the type and dimensions of a timber frame wall can slightly reduce the total environmental impact up to 10% in the cases considered. Of the cases considered, a timber frame wall composed of I-joists of 24 cm is preferable from an environmental perspective. Despite an equal material impact, I-joist are in general preferable compared to solid studs. This is due to the higher share of insulation material for the same wall and thus a lower energy use. Furthermore, a thinner timber frame structure combined with an extra insulation layer has a higher environmental reduction potential than enlarging the dimensions of the studs.

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